INVITED PAPER

Control, Computing and Communications: Technologies for the Twenty-First Century Model T

Tomorrow, it looks like cars will still run on gas and diesel, emissions will be lower, and there will be active safety devices aided by wireless communications.

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ABSTRACT | In the early twentieth century, the Model T Ford defined the desirable, affordable automobile, enabled by new technologies in mechanics, materials, and manufacturing. Control, computing, communications, and the underlying software are the technologies that will shape the personal mobility experience of the twenty-first century. While the Model T was self-contained, the external reach of wireless communication technologies will define the boundaries of the twenty-first century automobile, which will be only one component in a large intelligent transportation infrastructure. This paper reviews advances in control for safety, fuel economy and reduction of tailpipe emissions, and new directions in computing, communication and software, including the interaction of the automobile with consumer electronic devices and the intelligent transportation infrastructure.

KEYWORDS | Automotive software; chassis control; embedded computing; intelligent transportation; powertrain control; vehicle communication

I. INTRODUCTION

The Model T, first introduced in the year 1908, exemplified Henry Ford's vision of making the desirable affordable. Its real price to the consumer fell by two-thirds between 1908 and the early 1920s when its sales peaked [1]. The market responded—in 1910, the ratio of the number of persons to the number of automobiles (in the United States) was 19 000 and by 1920 this ratio had dropped to 11 [2]. The Model T came in nine different body styles, all mass produced on an identical chassis [3]. Its range of styles and low price made the Model T an icon of both "desirable, affordable" automobiles and of mass production early last century.

The historic position of the Model T at the beginning of the twentieth century provides an essential perspective on the role of control, computing and communications to the twenty-first century automobile. Since the time of the Model T, the automobile, its manufacturing processes and the context for its usage have all gone through several transformations [4]. These product, process and product context changes have been enabled by advancements in technologies, and in turn technologies have been shaped by the market responses to these changes. The 1908 Model T had no electrical technologies on it—its headlamps were lit by gas—and electronics and software were decades from invention. A modern automobile typically has 20–80 built-in microprocessors. Most of these are networked over standard automotive communications networks such as those based on controller area network (CAN) or media oriented system transport (MOST)

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specifications [5]. The changes and challenges associated with automobile manufacturing may be found in the literature [6]. The context for the use of the automobile has also undergone considerable change as computing and communications technologies distribute intelligence onto the roadways, our homes, offices, and most importantly into the hands of the consumer in the form of portable and wearable electronic devices. Although a complex computing system in its own right, the automobile is a just a *component* in an much larger intelligent transportation system (ITS) that involves the communications between other vehicles, the roadside infrastructure, and various vehicle service, infrastructure service and traveler service centers. An example of this is described in the ITS National Architecture maintained by the United States Department of Transportation [7]. With this type of computational intelligence embedded in the greater transportation system and in vehicles, a number of safety and convenience features become potentially realizable. Examples include automated highway systems [8]—that could both help reduce congestion and make driving less tedious and less stressful—and what is being envisioned for the 2008 Olympic Games in Beijing [9].

The engineering design of a modern automobile, at a high level, is dictated by two primary forces: government regulations and consumer demands. Government regulations, typically expressed in terms of objective requirements, are often set against a backdrop of a grand vision that includes terms such as "zero emissions" [10] and, in Europe, "zero fatalities" [11]. In complying with regulation, there is usually little room to make one automobile more desirable than another—this is the cost of doing business, and technology plays a critical role in meeting regulatory objectives cost efficiently. The advent of the microprocessor in the automobile (as elaborated in Section VI) for engine controls in the late 1970s was for the most part a result of such an objective. Unlike government regulations, consumer demands, that include both needs and wants, are often subjectively expressed and sometimes left unarticulated. This makes the interpretation of consumer demands difficult. Nonetheless, it creates considerable opportunity for competition and product differentiation.

In the early decades of the twentieth century, even the fundamental motive power of the automobile had not been established. Steam, electric, and even hybrid-electric vehicles such as the Woods "Dual Power" vied with the gasoline internal combustion engine as the powerplant of choice. By the 1920s, however, the spark ignited gasoline engine was the standard due to its low cost, high reliability, efficiency, and power-to-weight ratio. From a consumer perspective, the underlying architecture of the automobile has changed little since then: for the most part, one still fills the tank, turns the key, and in return receives unmatched personal mobility. As we look closer, however, much has changed, driven by consumer and societal expectations. Even the most luxurious automobiles of the early twentieth century do not match the "living room" comforts of the common twenty-first century family sedan. Today's consumer expects low interior noise, low vibration and harshness, customizable ride and handling, "plug and play" entertainment including wireless connectivity and associated road and travel services "anywhere, any time." Consumers expect improvements in fuel efficiency, safety, durability, reliability, comfort, and convenience with every new purchase. Society demands reductions in emissions, including greenhouse gases. Designing an automobile to meet the needs of consumers, while satisfying the expectations of society and the demands of regulators poses both challenges and opportunities.

In this paper, we review the role of computing, communications, and control systems in delivering automotive functions that meet both regulatory and consumer demands, and discuss emerging technologies that will shape the twenty-first century automobile including the combined vehicle and off-vehicle infrastructure that will define a large part of the personal mobility experience of tomorrow. This paper will describe automotive functions and features that we anticipate will become standard equipment as the concept of what is a desirable, affordable automobile keeps pace with the modern consumer who is increasingly immersed in a digital world, and who expects environmental stewardship, safety, and convenience. Reviews of other electrical, electronic, and software technologies may be found in the literature. See [12] for electrical power system architectures and [5] for in-vehicle communication technologies. This paper is organized as follows. Sections II and III address advancements in powertrain and chassis controls leading to improvements in performance, safety, fuel economy, and emissions. Section IV deals with intelligent vehicles. Section V surveys external communications, including the growth and ubiquitous presence of consumer devices and services in the context of the automobile. Finally, Section VI discusses issues in mobile computing.

II. POWERTRAIN CONTROL

Neils Bohr supposedly said, "Prediction is hard, especially if it's about the future."[1] One thing, however, is certain in the automotive industry: exhaust emissions from automotive engines will continually be reduced to lower and lower levels through the application of new powertrain technologies enabled by advanced electronic controls. Federal regulations require automobile manufacturers to achieve fleet averaged oxides of nitrogen (NO_x) emissions of 0.07 grams per mile by 2009. California requirements impose fleet averaged nonmethane oxygenated gas (NMOG, essentially, hydrocarbon, HC) emissions of 0.035 grams per mile by 2010. These requirements (which

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[1] Also, occasionally attributed to Yogi Berra.

represent a greater than 99% improvement from four-decades-ago preregulation emissions) can be accomplished by certifying vehicles to any of several specified emission categories, as long as the average of all vehicles sold achieves the mandated levels. California and Federal standards for the lowest categories of emitting vehicles impose limits of 0.02 grams per mile NO_x and 0.01 grams per mile NMOG. Below that is the Zero Emission Vehicle category wherein a vehicle may produce neither tailpipe nor evaporative emissions [13].

How will these ambitious requirements be met? Certainly, hybrid electric vehicles (HEVs) will play a part. Recently, major automotive manufacturers have committed to expanding HEV production [14], [15]. It has been estimated that there will be 52 hybrid vehicle models available by 2011, with sales reaching 780 000 units [16]. This, however, amounts to only 4.2% of U.S. vehicle sales. Other advanced technologies such as fuel cells offer promise in the long term, but the most common automotive powerplants will remain gasoline and, potentially, diesel engines that achieve very low emissions and high efficiency through precise control of combustion and aftertreatment. One reason for this is that incremental improvement in internal combustion engines has substantial economic benefit compared with adopting a new technology, considering the hundreds of millions of dollars of existing manufacturing capability that would have to be replaced. Consequently, it is estimated that the internal combustion engine will be the primary vehicle powerplant for at least the next 15 years [17].

Recent reviews of modeling and control for automotive powertrains may be found in [18]–[20]. Modern electronic engine controls regulate or diagnose over 100 different engine functions using multiple sensors and actuators. Fig. 1 illustrates some of the key elements in a direct injection spark-ignited gasoline engine. The functions of an engine control unit range from delivering the driver demanded torque to monitoring the emission control systems on board the vehicle, and from warming up the catalyst to purging the vapor from the fuel tank.

Typical sensors include sensors measuring crankshaft and camshaft position, intake mass air flow, manifold pressure, coolant and cylinder head temperatures, and exhaust gas oxygen sensors (located both before and after the catalytic converter). Conventional actuators include electronically controlled throttle, exhaust gas recirculation (EGR), ignition plug, and fuel injector. The advanced technology engine of our new Model T will very likely incorporate valve timing control (applied to intake valves, exhaust valves or both), turbocharger wastegate or variable vane control, cylinder deactivation control, fuel pressure control, swirl control for improved combustion, and intake

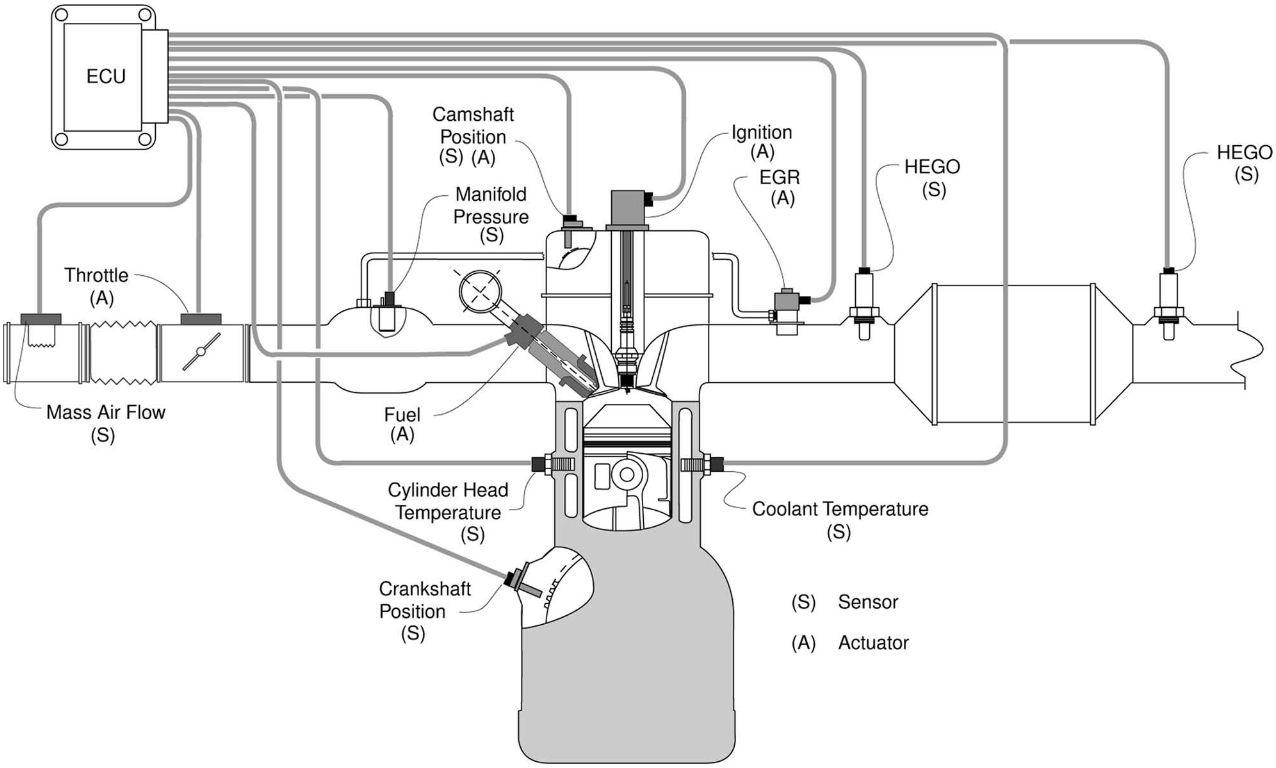

Fig. 1. *Electronic engine control system diagram.*

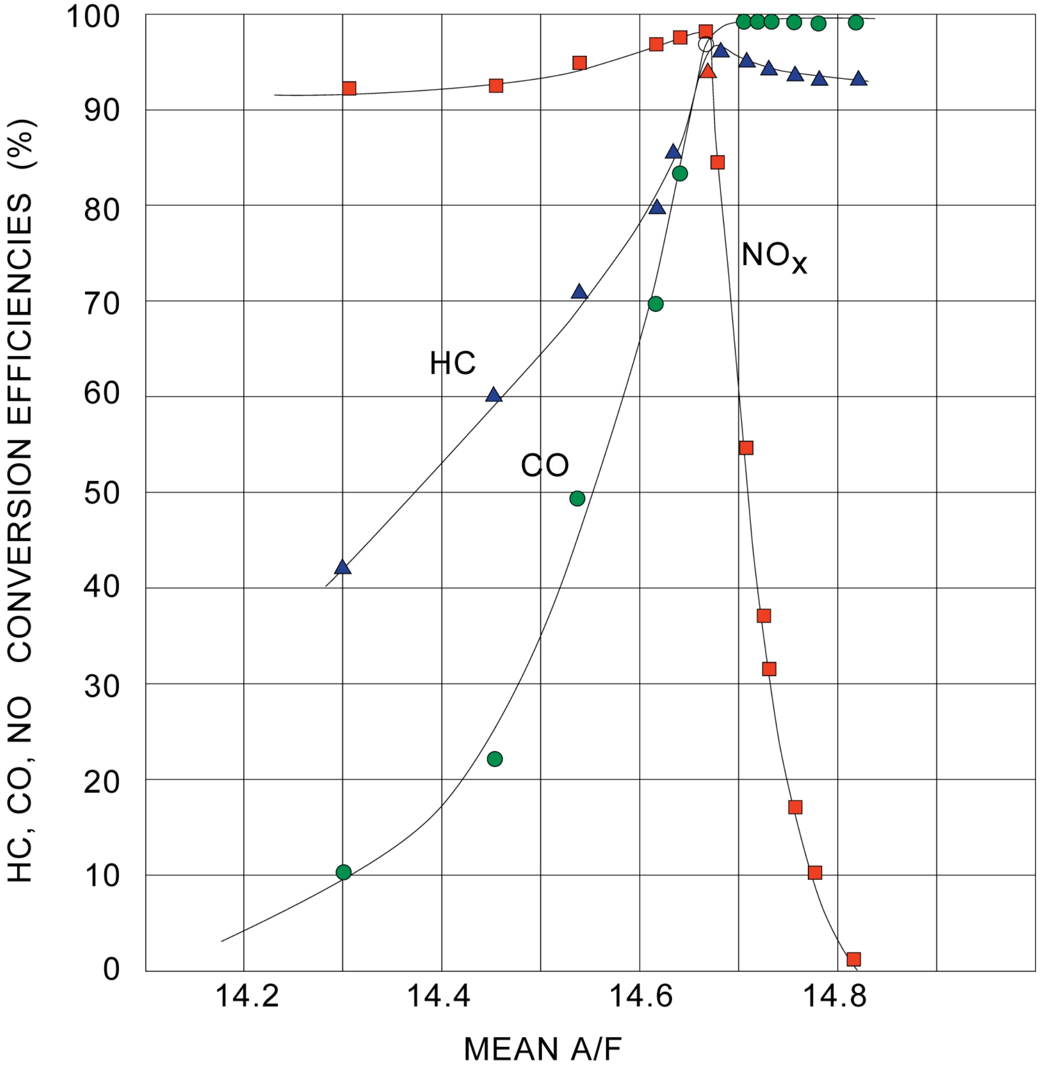

Fig. 2. *TWC conversion efficiency versus A/F.*

manifold runner control. It will almost undoubtedly take advantage of advanced sensing technologies like in-cylinder pressure or ionization measurements to optimize combustion.

For a conventional gasoline engine, the critical function for emissions control is precise air-fuel ratio (A/F) regulation in order to achieve maximum efficiency from the catalytic converter. This is underscored by Fig. 2 which illustrates that high simultaneous conversion efficiencies for the three regulated species (HC, NO_x and carbon monoxide, CO) occur only in a narrow band around stoichiometry for the three way catalyst (TWC) that is the standard emission control device. Dynamic A/F control of the conventional port fuel injected (PFI) engine[2] encompasses three fundamental aspects: accurate estimation of air charge, compensation for fuel puddling dynamics in the intake manifold runners and on the intake valves, and closed-loop regulation of A/F for high catalyst performance. The fact that many conventional gasoline engine vehicles meet near zero California emissions requirements is a testament to systems and controls development over the last three decades. In 2005, there were 35 vehicles that achieved this lowest emission level, and it is estimated that almost 3/4 of a million of these "partial zero emission vehicles" (PZEVs) will be on California roads by 2011. Cars achieving a PZEV emissions rating "have such tight pollution controls, and the burning of fuel is so complete, that in very smoggy urban areas, exhaust out of the tailpipe can actually be cleaner than the air outside" [21].

Precise closed-loop A/F control was made possible by the invention of the exhaust gas oxygen sensor (or heated

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[2] Port fuel injection refers to an engine in which fuel is injected in the intake manifold runner of each cylinder upstream of the intake valve.

EGO sensor, HEGO) in the 1980s. A HEGO is a binary sensor located in the exhaust system that indicates by its state if the mixture is lean or rich of stoichiometry, but not by how much. Due to the switching nature of the sensor, most of the standard control design methodologies based on linear system theory cannot be directly applied. Consequently, many of the HEGO-based A/F feedback control strategies are designed based on heuristic rules and physical insights. A significant advancement in A/F feedback control capability is the introduction of the Universal Exhaust Gas Oxygen (UEGO) sensor in production vehicles. Unlike the conventional HEGO sensor, the UEGO is a linear device that permits an estimation of actual A/F. It is reasonable to expect that over the next decade, this sensor will replace the ubiquitous HEGO permitting the application of advanced engine systems and control methods.

If emissions reduction were the only challenge facing the designers of our twenty-first century Model T, the conventional PFI gasoline engine would face little competition in the choice of powerplant. Fuel economy, however, is a competing objective that must be considered. Several technologies are available to improve the efficiency of our basic PFI gasoline engine. Each, however, increases both complexity and cost.

The most common technology is variable cam timing (VCT). Here, an electrohydraulic mechanism is employed to rotate the camshaft relative to the crankshaft and retard cam timing with respect to the intake and exhaust strokes of the engine. In this manner, the amount of residual gas trapped in the cylinder at the end of the exhaust stroke is controlled, suppressing NO_x formation [22]. In addition, VCT allows the engine designer to optimize cam timing over a wide range of engine operating conditions, providing both good idle quality (minimal overlap between the intake and exhaust events) and improved wide-open throttle performance (maximum inducted charge). Properly controlled, the variable cam can be used to operate the engine at higher intake manifold pressures, reducing pumping losses at part throttle conditions to provide a fuel economy improvement. As with all engine technologies, electronic control is essential since, uncompensated, the VCT acts as a disturbance to the breathing process, compromising drivability and substantially reducing its effectiveness in emission control. Four versions of increasingly complex, but increasingly effective VCT are available: phasing the intake cam, phasing the exhaust cam, phasing the intake and exhaust cams equally (dual equal), and phasing the two camshafts independently (dual independent). A low order nonlinear model of a dual-equal VCT engine is derived in [23]. The model forms the basis for active compensation of VCT induced cylinder air charge variation employing electronic throttle control (ETC) [24]. As the number of degrees of freedom in VCT increase, the greater challenge becomes optimization rather than regulation. Experimental characterization of a dual-independent VCT engine may be enormously time consuming (emissions and fuel consumption are a function of intake cam position, exhaust cam position, ignition timing, A/F, engine speed, engine torque, and potentially several other variables, all of which must be measured), and online minimization of fuel consumption consistent with emissions generation and performance is complex [25].

Substantial improvement in efficiency with respect to the conventional PFI engine can be attained through the application of so-called "lean burn" technology. Such engines operate unthrottled at very lean A/F mixtures (A/F much greater than stoichiometry) for low and part-load conditions to reduce pumping losses, improve fuel economy and lower CO_2 emissions. A direct injection stratified charge (DISC) engine, like a diesel, injects fuel directly into the combustion chamber. It is different from a conventional PFI engine in several aspects. Most importantly, the DISC engine can, depending on speed and load, operate in one of three combustion modes: homogeneous stoichiometric ($A/F \approx 14.64$), homogeneous lean (A/F between stoichiometry and about 20), or stratified ($A/F \geq 20$). A homogeneous A/F mixture is achieved by injecting fuel early in the intake stroke, while stratification is achieved by injecting late, during the compression stroke [26]. The torque and emission characteristics corresponding to homogeneous and stratified operation are so distinct that different control strategies are required to optimize performance in the two regimes [27]. Note also that, in addition to the usual control variables such as throttle position, ignition timing, EGR, and fueling rate, the DISC engine requires new inputs including injection timing, fuel rail pressure, and swirl control at a minimum [28]. Finally, to accommodate the ultra-lean A/F operation of the direct injection engine a special, actively controlled catalytic converter called a lean NO_x trap (LNT) is used to manage emission of the oxides of nitrogen. The LNT stores NO_x under lean and stratified operating conditions, and must be periodically purged at stoichiometric or rich A/Fs to regenerate its storage capacity. To achieve the best tradeoff among competing requirements such as fuel economy, emissions, and driveability, the LNT control strategy must manage the purge starting time and duration, and purge conditions (such as A/F), and at the same time provide a bumpless transition between the lean and purge modes. The main challenges of LNT control stem from the lack of on-board measurements of key variables and uncertainties in the characteristics of key components. The NO_x storage capacity of the LNT, one of the most critical parameters for control design and calibration, varies dynamically. In particular, the trap is susceptible to sulfur poisoning [29] and the capacity of the trap is reduced as sulfates accumulate. In addition, ambient conditions and component-to-component variations can affect the LNT operation and lead to deteriorated performance. Control oriented representations of the LNT may be found in [30] and [31]. In the absence of real-time measurements, the aftertreatment control has to rely on feedforward and model-based control, making the system performance vulnerable to uncertainties and model inaccuracies. LNT control incorporating online parameter identification and adaptation is described in [30], [32], and [33].

Each of these advanced technology engines has as its objective an increase in fuel economy by the reduction of throttling losses similar to the performance achieved naturally by diesel engines. Might not, then, the next generation Model T have as its motivation a twenty-first century diesel?

Diesel engines offer superior fuel economy compared to their conventional gasoline counterparts. Their drawbacks are associated with higher cost and complexity of the aftertreatment system. Despite earlier skepticism, diesel engines have achieved a remarkable passenger car market penetration in Europe thanks to technology improvements. The consensus is that their penetration in North America will grow too, albeit at a slower pace due to differences in fuel cost and taxation. Diesel systems, however, face arduous challenges in emissions control.

Diesel tailpipe emissions are primarily HC, NO_x and particulate matter (PM) consisting of soot resulting from incomplete combustion. Particulate emissions are controlled by diesel particulate filters (DPFs) which store soot by filtering it from the exhaust gas, but must be regenerated periodically by exposure to high temperature or by catalytic means. Since diesel combustion temperatures are relatively low, heating the exhaust gas to a temperature where soot will burn typically requires an additional device. Electric heaters or fuel burners are an option but are costly and problematic [34]. An alternative is a diesel oxidation catalyst (DOC) placed upstream of the DPF to heat the exhaust gas via exotherm from chemical reactions [35]. Typically, a reductant such as fuel is injected upstream of the DOC leading to the desired exothermic oxidation. Usually, temperature measurements in the exhaust are available for DPF monitoring, but the slow temperature dynamics of the combined DOC-DPF system make aggressive feedback control difficult. Consequently, temperature control relies in general on open loop methods. Regeneration is typically initiated based on the time since the last regeneration or an indication of DPF loading such as a measured pressure difference across the DPF.

Currently, diesel NO_x emission control addresses only engine out emissions, using large amounts of EGR to control combustion temperature and limit formation. To meet the stringent emission requirements effective at the end of the decade, actively controlled diesel aftertreatment is essential. There are three candidate technologies: Lean NO_x traps, active lean NO_x catalysts (ALNC), and selective catalytic reduction (SCR) using urea.

A promising technology is the LNT. As with the direct injection gasoline engine discussed previously, the lean NO_x trap must be periodically regenerated by operation at stoichiometric or rich conditions. The characteristics of diesel combustion, however, are such that visible smoke and increased PM are generated when the engine is operated at A/F less than approximately 20 : 1. Furthermore, the efficiency of the LNT is temperature-dependent, so low temperature diesel combustion makes operation of the trap more difficult [36]. Providing reductant to the LNT for regeneration via rich operation of a diesel engine, although feasible, is a difficult control problem [34]. Combustion is inefficient at rich conditions and significantly larger amounts of PM are produced. This leads to more frequent regeneration of the DPF and potential durability issues due to deposits. Another potential approach, injection of fuel into the exhaust, is also challenging due to difficulty in achieving proper atomization of the fuel to prevent reductant breakthrough.

Whereas the LNT operates cyclically, periodically trapping NO_x during lean operation and then converting and regenerating under rich conditions, active lean NO_x catalysts and SCR catalysts operate continuously. The ANLC requires the delivery of supplemental hydrocarbons, usually diesel fuel injected upstream of the catalyst to provide the reducing agent. In [37], a control oriented gray-box mathematical model of the ALNC is developed that represents the phenomena relevant to NO_x reduction and HC consumption on the catalyst. Dynamic programming is then applied to determine the optimal tradeoff between NO_x conversion efficiency and injected hydrocarbon.

In SCR catalysts, urea is injected into the exhaust stream [38]. Urea decomposes to ammonia, which serves as the reductant in the conversion of NO_x. Accurate control of urea injection is critical for conversion efficiency and to avoid breakthrough of ammonia, which can lead to a foul odor at the tailpipe. The complex behavior of the SCR catalyst [39], as well as the transient nature of automotive applications, complicates the control problem. Observer-based feedforward control, along with feedback from a NO_x sensor is a potential solution [40]. Compensation for NO_x sensor sensitivity to ammonia, however, must be considered for effective feedback control. NO_x conversion with SCR technology is efficient, but implementation requires a reductant distribution and storage system, as well a change in societal infrastructure to support refilling. These issues may limit application in the United States.

The other key powertrain component is the transmission. Reference [41] discusses several emerging technologies that have fuel economy, performance, and emission benefits, specifically: continuously variable transmissions (CVTs), dual clutch transmissions (DCTs), and automated manual transmissions (AMTs). In each case, close attention to dynamics and control is identified as essential in achieving the full potential available from the hardware. Recently, CVTs have seen production implementation in several vehicle lines due to the fact that they permit engine operation at the most efficient operating point. There are a number of CVT designs, a common one being the belt- or chain-drive CVT. A CVT of this type has the control challenge of providing fast ratio control, while maintaining adequate clamping force on the belt to avoid slipping without introducing excessive efficiency losses. In [42], a robust controller design is presented that minimizes clamping forces to improve efficiency by up to 30% at low engine torque. CVT characteristics may be used to facilitate or enhance the operation of advanced technology powerplants. In [43], a CVT is used to manage torque during mode transitions in a DISC engine. In [44], a CVT is combined with a parallel HEV and the system operation (throttle angle and CVT ratio) optimized for minimum fuel consumption. Reference [45] provides a detailed examination of CVT architectures for HEVs. Automated manual and dual clutch transmissions attempt to achieve the efficiency of a conventional manual transmission with the advantage of automatic shifting, at the cost of complex and calibration-intensive software to provide smoothness and performance. Automated manual transmissions are structurally similar to manual transmissions, with a key difference that the mechanical clutch is electronically controlled, thus facilitating automatic shifting. On the other hand, by adding one additional clutch, as is the case in the dual clutch transmission, it becomes possible to achieve the shift quality of the standard automatic transmission. Since the dual clutch transmission eliminates the need for torque converter and various clutches and bands, it is characterized by relative hardware simplicity and efficiency. This reduced hardware complexity is accommodated by increase in control system software complexity and sophistication. The use of feedback control algorithms, adaptation and of advanced control concepts will be essential [46] in this and other software-intensive applications to achieve superior performance and robustness despite vehicle-to-vehicle variability, component aging, and other uncertainties.

While this section mostly focused on powertrain control, powertrain diagnostics will continue to account for a significant share of the computational burden of future vehicles, comparable to that of powertrain control itself. The increasing sophistication of estimation and pattern recognition algorithms employed for diagnostics and new sensor technologies, such as ionization current sensing, are likely to shape future developments in this area. For instance, a particularly challenging diagnostic function is engine misfire detection, which at the present time is almost always based on crankshaft position sensor measurements. Neural networks have recently been applied to sort out the effect of misfire from torsional vibrations of the crankshaft. This application was described in concept some time ago [47], and it recently reached production in Aston Martin 8- and 12-cylinder engine models.

Whether diesel, gasoline or hybrid, the powertrain in the next-generation vehicle will be distinguished by its complexity and the critical nature of the electronic controls required to simultaneously achieve driveability, improve fuel economy, and lower emissions.

III. DRIVING ADVISORY, ASSISTANCE, AND ACTIVE CHASSIS CONTROL

Electronically enhanced driving dynamics that improve safety and increase driving pleasure and comfort are a source of product differentiation for car manufacturers. Dynamic stability systems such as antilock brakes and traction control are common on even moderately priced vehicles [48]–[50]. Yaw stability control systems [51], [52], which use differential braking and engine torque reduction, and rely on inertial sensors measurements, are standard on many sport utility vehicles [53]. Based on a recent NHTSA study [54], these systems, also known as electronic stability control (ESC), reduce single vehicle crashes in passenger cars by 35% and in sport utility vehicles by 67%. Roll stability control (RSC) systems [55] have been recently introduced [56] to further enhance yaw stability and mitigate rollover using an additional roll rate sensor. These and other individual chassis control features have proliferated in large part due to the development of reliable and inexpensive inertial sensors, based on microelectromechanical systems (MEMS) technology. Our future Model T will undoubtedly contain these and additional safety enhancing technology, perhaps even steer- and brake-by-wire, to provide vehicle performance that accounts for the environment, extends stability, and improves the driving experience and comfort. But the major challenges will be to robustly estimate vehicle states, and to integrate and coordinate chassis control, active safety[3] and emerging navigation and information systems.

Chassis control and active safety systems use sensed information to advise or warn the driver of an impending situation that requires attention, or even assist the driver by assuming partial control of the vehicle. Advisory systems include tire pressure monitoring, driver "falling asleep" or "eyes off the road" state monitoring, lane departure warning, curve detection, blind spot detection, obstacle detection and emerging safety features such as pre-crash sensing wherein the driver may be alerted to an impending accident and safety belt pre-tensioners activated before the collision. Active (sometimes called "adaptive") cruise control (ACC) is an example of driver assistance currently in production on several luxury vehicles. ACC is an extension of conventional speed control that uses a radar or a laser to automatically maintain a minimum timed headway from a leading vehicle in the same lane using throttle and brakes. The vehicle returns to the set cruise speed in conventional speed control mode when the target vehicle clears. An extension of ACC

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[3] Active safety systems provide warning or intervention to help the driver avoid accidents or, if an accident is unavoidable, to mitigate accident severity.

technology, the so called Active Collision Mitigation by Braking, is an active safety driver assistance feature which aggressively engages the brakes to mitigate an imminent collision, while warning the driver. Further examples of driver assistance systems include parking assistance, lane changing assistance, lane keeping assistance, yaw control, anti-rollover control, and other ESC systems that increase the range of operation over which the vehicle behaves predictably, improving both safety and comfort [57], [58]. For example, during normal driving on a dry road, a vehicle responds to accelerator, brake and steering consistently with the driver's intent. This may not be the case in extreme driving situations where the physical constraints on the contact force between tires and the road become active. In this situation, the electronic control system, reliant on appropriate actuators and sensors, interferes to mitigate the constraints, while providing vehicle response as close as possible to the driver's perceived intent, or at least in such a way as to enable the driver to recover vehicle control. This is conventionally accomplished by controlling individual wheel braking and through engine torque reduction [59]–[62]. More advanced systems may also utilize active steering whereby the vehicle steering angle is modified relative to the angle commanded by the driver through the steering wheel. Ultimately, steer-by-wire eliminates the mechanical linkage between the steering wheel and the front axle, and the driver's steering angle is perceived by the control system as the command reflective of the driver's intent. In active steering systems, the mechanical connection is still present but an additional angle, determined by the control system, is superimposed by an actuator such as an electric motor connected through a planetary gear set [63]. In other systems, steering torque is modifiable [64]. Active steering, in combination with brake and throttle intervention, improves yaw control, and thus dynamic stability system performance. Careful design is required to coordinate brakes, engine torque, and active steering in order to achieve this benefit [60], [65]. These chassis control features have already been shown to be effective in reducing the number of single vehicle crashes, including rollovers [66], [67]. Optimal coordination between steering, individual wheel braking, engine, transmission and other active subsystems (such as an electronic differential and an active or semi-active suspension), as well as traffic and road information systems will be exploited to a greater degree in the future. Tire forces required to ensure the desired vehicle motion will be determined at each of the four wheels. These forces will then be cascaded and allocated to individual actuators while taking account of constraints; it is likely that this allocation will rely on a fast constrained numerical optimization performed on-board the vehicle. In addition, sophisticated estimation algorithms will be deployed to accurately calculate unmeasured vehicle states from available information obtained by fusing sensor measurements and road and traffic information obtained through communications and navigation systems. Improved vehicle and road/tire state estimation will enable more optimal vehicle performance. For instance, an active or a semi-active suspension may control the tire normal force as needed to yield desired longitudinal and lateral tire forces which, in turn, enhance vehicle stability and improve ride and handling [68]. If a preview information of road profile is available from future communications and navigation systems, the control of the suspension system can be optimized to accommodate oncoming road conditions [69].

From a practical standpoint, promising control methodologies for achieving integrated vehicle control include reference governors [70] and model predictive control (MPC) [71], where the latter was successfully applied in process control industry for years. One of the impediments to deploying MPC for chassis and powertrain control, are chronometrics and memory limitations of typical microcontrollers used on-board of production vehicles. This obstacle is being gradually overcome due to increase in microcontroller computing power, on one hand, and, on the other hand, due to emergence of new MPC paradigms, such as explicit hybrid MPC [72]. These new theoretical developments in the area of MPC have led to an in-vehicle demonstration of its applicability for improved traction control [73]. Other recent automotive applications of these techniques include control of electromechanical actuators [74], control of direct injection engines [75], control of semi-active suspensions [69], and active steering control [76].

Achieving the benefits of integrated vehicle control requires addressing the challenges of distributed, possibly asynchronous, networked communication among cooperating control features (antilock braking, traction control, yaw control) that may be developed by different suppliers and reside in different microprocessors. New theory is required to assure stability, performance and robustness in the face of communication constraints and nondeterministic behavior [77]. On the software side, cooperative industry efforts are underway to confront practical issues of interface compatibility and architecture to support software integration. The automotive open system architecture consortium (AUTOSAR) has as its objective the establishment of an open standard automotive architecture to facilitate integration of functional modules from multiple suppliers [78]. A vehicle software architecture implementing supervisory control to coordinate vehicle functions and promote interchangeability of software components was developed by Robert Bosch GmbH in the late 1990s, and has been used to establish a unified powertrain control structure supporting both diesel and gasoline engines [79], [80]. Recently, the complexity of HEVs with the necessity of coordinating multiple power sources and operating modes has required the development of structured methods of managing engine, motor, transmission, battery, regenerative brakes, and other vehicle subsystems [81]. Finally, fault-tolerant bus communication with guaranteed access and message latency will most likely prove essential for critical distributed systems such as steer-by-wire.

With the growing electronic content and rapidly evolving x-by-wire (e.g., shift-, brake- and steer-by-wire) functionality, increasing attention is being paid to ensuring adequate operation of the vehicle in the event of significant degradations and faults in sensors, actuators, computing or networking components. The degradations are detected by the control system and, if necessary, the overall system is gracefully reconfigured to a safe state, where a restricted functionality of the vehicle (such as lower engine speed, gear restrictions, or a limp-home mode) is still available to the driver [82]. As no mechanical backups may be available for the future x-by-wire systems, the fault-tolerant behavior of the vehicles may be assured through either hardware or analytical redundancies in the vehicle hardware subsystems [83] and by an appropriate design of electronic, computing and control system architecture [84], [85]. For instance, the calculation of the key signals may be performed redundantly on different processors to detect discrepancies, sensor measurements may be checked and fused with analytically generated estimates, and periodic system self-checks can be automatically conducted involving different (or watchdog) processors challenging each other to perform predefined calculations. Ensuring fault tolerance through analytical redundancy requires dealing with challenges of nonlinear and dynamic relationships among sensors during a wide range of maneuvers with significant uncertainties [61], [86].

IV. POWERTRAIN AND CHASSIS CONTROL OPPORTUNITIES IN INTELLIGENT VEHICLES

Intelligent transportation systems (ITSs) refers to intelligent infrastructure and intelligent vehicles (IVs) that use communication and controls to reduce traffic congestion, provide driver information, and improve safety through collision avoidance and driver assistance. One aspect of IV is the integration of digital road maps, the satellite-based global positioning system (GPS), and other real-time ITS infrastructure data such as traffic conditions, with existing vehicle dynamics sensors (radar, gyroscope, yaw) to evaluate (and even predict) the driving environment. The result is an intelligent vehicle incorporating such functions as advanced ACC that use navigation data (road classification, number of lanes, curvature, etc.) to adjust the system behavior and provide curve speed and lane keeping assistance, or an adaptive powertrain management resulting in improved fuel efficiency [87]–[90]. Consider two potential intelligent vehicle functions using GPS: lateral stability control, and predictive control for improved fuel consumption.

ESC systems require yaw rate and vehicle slip angle (slip angle is the angle between the vehicle heading and the wheel heading and is determined by the vertical load on the tire, coefficient of friction of the road and longitudinal slip of the tire). Gyroscope measurements provide yaw rate information, but slip angle, which is the most important vehicle dynamic state, is not so easily measured. Typically, slip is estimated using a vehicle model and observer, and a variety of techniques have been employed for this purpose [50]. In [91]–[97], both yaw rate and slip angle are estimated based on measurements of steering wheel angle, wheel speed, and lateral acceleration. Such model-based methods, of course, suffer from errors resulting from modeling uncertainty, changing vehicle parameters over time, and operation outside the (usually linear) range of model accuracy. High accuracy differential GPS, however, in combination with conventional vehicle dynamics sensors, may be used to determine vehicle side slip without relying on a model [99]–[101]. In [102], yaw rate measurements are integrated with two-antenna GPS to determine vehicle attitude, slip angle, and longitudinal velocity using a kinematic vehicle model and Kalman filter to provide a higher update rate estimate of vehicle states than would be available using GPS alone. In [103], the authors develop a real-time parameter estimation algorithm using differential GPS and yaw rate to determine tire-road friction coefficient, thus identifying slippery road conditions that can be communicated to the driver. Various use of GPS for vehicle dynamics control are also discussed in [104].

Another potential application of GPS, in combination with digital road maps and other ITS information is predictive powertrain control. In [105], the authors use a three-dimensional road map plus GPS to evaluate the terrain 4 km ahead of a Class-8 commercial vehicle. An optimization routine determines the best vehicle speed with respect to fuel consumption and travel time. A predictive cruise control is proposed that accelerates the truck prior to encountering an uphill grade, and slows down before achieving the downhill slope. It is interesting to note that no environmental influences (such as other traffic) are considered. Nonetheless, a 4% improvement in fuel consumption was achieved (in simulation) for a representative test route near Portland, OR. Perhaps more practically, predictive control based on GPS may be useful in achieving real-world optimal fuel consumption for HEVs [106]. The HEV advantage is that the two power sources (internal combustion engine plus electric machine) can be used to minimize fuel consumption constrained by emissions and maintenance of battery charge. Typical power management strategies for HEVs can be roughly classified into three categories. The first type employs heuristic techniques such as rule-based methods, fuzzy logic, or neural networks [107], [108]. The second approach is based on static optimization. Here, electric power is generally expressed as an equivalent steady-state fuel rate in order to minimize an overall energy cost [109], [110]. The optimization scheme determines the proper split between the two energy sources using steady-state efficiency maps. The third approach considers the dynamic nature of the system components [111]–[113]. Dynamic programming methods for HEV power split ratio (PSR) optimization are reported in [114]. One issue with all of these optimization approaches is that the resulting control policy is optimal only over the drive cycle to which the method was applied, and there is no guarantee that the resulting strategy is optimal (or even charge sustaining) over other cycles. This was addressed in [115] where the authors take a stochastic approach to PSR optimization that is both causal and cycle independent. Specifically, the power demand from the driver is modeled as a random Markov process and the optimal control strategy is obtained by stochastic dynamic programming. Integration of ITS information, however, means that an electronic preview, of the *actual* route may be available to the controller.

In [116], a fuzzy logic-based control system is developed to manage the PSR for a charge-sustaining HEV taking into account future driving conditions based on GPS and ITS traffic information. The control structure consists of two parts. The main controller uses current operating information including battery state-of-charge (SOC) and static engine efficiency and emission maps to establish the PSR at each instant. A *navigation controller* uses traffic and GPS information to predict the future driving state of the vehicle and modify the PSR to charge the battery (if, for example, it is predicted that the vehicle will change from highway to city driving where the electric motor will be required) or to deplete the battery for improved fuel economy in anticipation of a down grade where regeneration may be expected.

In [117], MPC is applied to determine optimal PSR and transmission gear for a mild hybrid vehicle incorporating a small integrated starter-alternator of about 10 kW. The MPC algorithm is based on a simplified drivetrain model containing SOC as the only state variable. Inputs to the algorithm include GPS position and velocity along with navigation data such as elevation, speed limit, number of lanes, and road curvature. Local traffic information was incorporated using ACC-type radar to detect in-lane obstacles. The dynamic programming approach to implementing the MPC algorithm is described in [118]. The authors focus on reducing the search space to make the real-time implementation feasible. In [119], the preview of road conditions and dynamic programming are used to optimize fuel economy through a gear disengagement and fuel-cut during downhill descents. In the future, the implementation of these and other advanced and computationally intensive control algorithms may be facilitated by rapidly evolving computing hardware technologies such as field programmable gate arrays (FPGAs) developed via a hardware definition language (such as VHDL) directly from a C code or Simulink specification of the control algorithms [120].

V. EXTERNAL COMMUNICATIONS

A comprehensive review of in-vehicle communication systems is contained in [5]. A growing area of importance to the twenty-first century automobile is external communications as indicated by the development of standards for wireless personal area networks or PAN (IEEE802.15 [121]), wireless local area networks or WLAN (IEEE802.11 [122]), and broadband wireless metropolitan area networks or WMAN (IEEE802.15 [123]). We review external communications for the automobile from the viewpoint of a consumer who will soon expect the same quality of connectivity on the road as experienced elsewhere. We address two aspects of connectivity based on emerging PAN and WLAN standards: connecting consumer devices to automobiles and connecting automobiles to off-board infrastructure.

Consumers have already begun to experience the benefits of PAN standards in the form of numerous Bluetooth [124] devices—including mobile phones, computer printers, keyboards, cameras, and toys. Hands-free telephony with Bluetooth wireless technology is already emerging as an option in automobiles. While wireless connectivity is convenient, in most cases, it is not essential and sometimes a wired connection is preferred since this gives the option of recharging devices within an automobile. An emerging choice for wired connectivity in the automobile is the Universal Serial Bus or USB [125], based on its widespread adoption on portable electronic devices. Device connectivity in an automobile is an important design and engineering consideration because of the explosive growth of portable consumer devices. While both consumer trends and connectivity technologies in homes [126] are good reference points for engineering solutions in the automobile, the automotive design challenges are exacerbated by several factors. These include real-life usage conditions (extreme operating conditions) that impose durability requirements, and the large mismatch between automobiles and consumer devices in terms of product development time and life cycle duration, collectively referred to as clockspeed [127].

With the increasing presence of WLAN (popularly known as WiFi) technologies at offices, homes, businesses and public places (commonly referred to as hot spots [128]) consumers might expect these technologies in automobiles. While WLAN technologies are gaining acceptance in the stationary infrastructure, the most deployed form of wireless connectivity to the automobile today is automotive telematics [129] and this is based on cellular telephony. To the consumer, automotive telematics is a service that at the very least comes with the reassurance of providing both emergency help and roadside assistance. Automotive telematics may be defined as an end-to-end telecommunications and computer-based content provisioning service where one end always involves an automobile. With the advancement in peer-to-peer technologies, alternative approaches to traditional cellular carrier-based telematics are emerging, including the use of vehicles as probes of real-time traffic conditions. Telematics, on a global scale, is beginning to encompass toll collection, fleet vehicle management, stolen vehicle tracking, automatic collision notification, and location-based services and remote diagnostics. In addition to the road and journey related services, telematics are being augmented by general information and entertainment related services to which consumers may directly subscribe through their wireless service providers.

While cellular technology is making rapid strides and is still a core enabler of telematics, it is not the only path to the promise of the Internet automobile of the twenty-first century. Today, WiFi is rapidly being adopted [128] the world over and its application to the automobile is already being envisioned [130]. Meanwhile, worldwide interoperability for microwave access (WiMAX) based on the IEEE802.16 [123] WMAN standard is emerging as an alternative to cellular telephony and WiFi technology for the last mile of broadband connectivity. A recent technical development in the area of automotive infrastructure development is mesh networks [131], which were first developed by the military to route communications between nodes or other wireless networks. Mesh networks can be very reliable and have useful properties, because they are self-healing and can still operate even when a node breaks down or a connection is lost. Thus emerging cellular, WLAN and WMAN technologies will undoubtedly offer the new essential features for the twenty-first century automobile.

To prove the feasibility of a nationwide wireless communication infrastructure for land transportation in the United States, government authorities, automobile manufacturers, and suppliers have come together to establish the Vehicle & Infrastructure Integration (VII) consortium [132].

Vehicle Manufacturers, the United States Department of Transportation (USDOT), and the American Association of State Highway and Transportation Officials (AASHTO) are working together to determine the feasibility of a national roadside-to-vehicle infrastructure based on the IEEE 802.11p data link standard, known commonly as dedicated short range communication (DSRC) [133], [134]. Current DSRC related standards efforts also include the IEEE 1609.1, IEEE 1609.3, and IEEE 1609.4 standards for application management, network services, and medium access control, respectively. In addition, there is also the IEEE 1609.2 (formerly IEEE 1556) standards work on DSRC related security. DSRC is a general-purpose short-to-medium range dedicated communications service that can support both public safety [135] and private operations in roadside-to-vehicle and vehicle-to-vehicle communication environments. The proposed DSRC enabled infrastructure would enable major new safety features that would also significantly change the way consumers receive news, weather, travel, and other information in their vehicles. DSRC roadside units would be placed along highways and at intersections in major metropolitan areas across the country. The roadside units would act as hot spots to provide wireless services to the vehicle as it travels. Linking vehicles to roadside hot spots will provide next-generation safety features including real-time alerts such as icy road warnings, railroad crossing alerts, road construction delays, and more in order to minimize collision incidents. Although the infrastructure proposal is still in its early planning stages, the initial goal is to implement DSRC roadside units at highway intersections in major metropolitan areas nationwide by 2010 and roll out to all intersections soon after.

The confluence of in-vehicle and external communication technologies will lead to new information, entertainment and safety services such as the in-vehicle display of roadway emergency warnings to actively mitigate collisions at intersections. Another implication of vehicle-based wireless communications technologies is vehicle-to-vehicle (V2V) cooperation for improvement of safety and traffic flow [136].

With the twenty-first century automobile connecting to the external infrastructure, the human safety and convenience requirements that were once associated with the physical or mechanical aspects of the automobile design have now begun to apply to wireless services as well. This translates to quality-of-service (QoS) demands on wireless services that go beyond the requirements of similar services in other mobile contexts (pedestrian, in-office, at-home). Some factors that make the automotive context unique, both from a consumer and an industry standpoint are:

1) *Safety:* For wireless (cellular, WLAN, or MLAN) communications to be useful for automatic crash notification, the service must always be available and scalable (to rush hour volumes of traffic, for example) in addition to being reliable in terms of signal quality and service. The demands are less critical for nonemergency roadside services.

2) *Security and Privacy:* From the consumer standpoint, there is concern that they may unwittingly "accept" a connection to an unknown service or mobile device (say from an adjacent car or the road side). The industry, on the other hand, is concerned about possible corruption to vehicle systems on account of unauthorized mobile device or service interactions. With automobiles beginning to be used as probes, to monitor traffic or weather conditions for example, there is a new privacy need that is emerging. This has to do with being able to enroll a particular automobile as a probe, while also protecting the identity of the individual who is responsible for the automobile.

3) Usability: To ensure no compromise to safety, automotive ergonomics and human factors considerations place stringent requirements on ease-of-use. Latency in human machine interactions, or human effort measured in time (in seconds) taken to complete a task may not exceed certain industry established limits, for example. In automotive applications, the human user needs to complete tasks in a limited amount of time. An example of this is the "15 second rule" [137] which specifies the recommended maximum amount of time for drivers to complete navigation tasks that involve displays and associated decision making. Another aspect of usability is based on the role of the vehicle occupant: what a driver may or may not be able to do versus the passenger. Although the driver may have a video display for navigation purposes, entertainment video content may not be viewable unless the vehicle is in the "park" position, for example. To differentiate themselves, the automakers may have their own proprietary usability requirements for added convenience. As a result, it may be easier for the consumer to switch between digital content sources (AM/FM/CD/Satellite Radio/USB/Bluetooth-based mobile devices) in some vehicles compared with others.

4) Digital Rights Management (DRM): A comprehensive review of DRM may be found in [138] and [139]. Downloading and streaming (distributing) digital content in an automobile is considered a convenience feature. Given that there are a number of incompatible technologies today that implement DRM, a consumer concern would be one of seamless connectivity—without having to be burdened with being responsible for the DRM compatibility between the sources of content and the playback systems in the automobile. If the context were not the automobile but a home or office, consumers would have the choice of easily upgrading their incompatible units, but in an automobile such upgrades may or may not be feasible. Even if all systems were compatible at the time the automobile was purchased, there is every likelihood there will be periodic upgrades to the DRM system (initially software only but eventually hardware, too) over the course of the life of the automobile (typically 10 years or 150 000 miles).

5) Electromagnetics: Antenna design, placement, gain and transceiver sensitivity to minimize noise levels, propagation delays, fading and interference all impact the delivery of wireless service to the automotive consumer. Radio frequency (RF) noise sources are found in vehicle electronics (e.g., the powertrain control module and the ignition module) and in external in-band or near-band communications. The use of mobile devices such as phones and handheld navigation devices in the vehicle with their own antenna systems exacerbates the RF issues, especially if the devices are placed on the floor of the interior cabin below the "belt line" of the vehicle or below windshield glass (which attentuates RF signals). Automotive manufacturers have several options to minimize electromagnetic interference (EMI) and electromagnetic compatibility (EMC) issues. These include pure mechanical fixtures to house mobile devices at locations optimized to minimize EMI and EMC issues, electrical solutions involving enhanced shielding of traditional RF noise sources, and software application-level arbitration mechanisms that temporarily turn off wireless technologies that may not cohabit well. An example of this would be using software to turn off a WiFi transceiver, while a higher priority Bluetooth-based phone service is in use.

6) Service Discovery: High automobile speeds, especially relative speeds between vehicles traveling in opposite directions (which could exceed 300 km/h, in many parts of the world), the harsh automotive electromagnetic environment, the limited attention that the driver has for tasks other that driving down the road, are some of the factors that place stringent demands on discovery of communications services within an automobile.

In response to the opportunities and challenges posed by connectivity, the automotive manufacturers are beginning to implement solutions in the form of connectivity modules. One example of this is a Bluetooth module that allows hands-free wireless telephony. Such solutions are not only a means of addressing safety, security, and privacy needs, but also as a way to address the clockspeed [127] challenge of decoupling the automotive development cycles from those of consumer electronics—so consumers may be able to use their new mobile devices and services with their relatively old automobiles.

The key to the promise of connectivity in the twenty-first century automobile will be in the ability of the automobile to refresh its digital content and appropriate silicon content. The emerging tools of product life cycle management will play a critical role in this regard. With all the external communications technologies converging to the automobile, periodic software upgrades to connectivity modules will become a growing need. Hardware upgrades will be needed too, but as is true of the personal computer, these will be less frequent than software.

VI. COMPUTING

Henry Ford's Model T had no need of the yet to be invented microprocessor to perform its intended functions. The Model T of the twenty-first century, on the other hand, will be highly dependent on computing to meet fuel economy and emissions standards, to comply with safety regulations and to provide the levels of convenience, comfort, and information that are expected of even the most basic automobiles. Today's automobile has anywhere from 20 to 80 microprocessors built into it, and the software in those microprocessors provides 500–600 customer visible features.

The microprocessor first appeared in production vehicles in 1978. It was a 12 bit processor with 1 Kb of memory. The software that ran on this processor controlled only the ignition timing and EGR to the engine. The processors in today's car control everything from the engine to the windshield wipers. They range from 8 bit processors with 1 Kb of flash memory and 128 bytes of RAM to 32 bit processors with double precision floating point hardware and 1 MB or more of memory. Most of the growth in in-vehicle computing during this period has resulted from the replacement of mechanical control systems by software directed electronic control systems, but some of it, especially recently, results from the introduction of new features into the vehicle, such as adaptive cruise control and navigation systems. In the near future, additional growth may come from the importation of consumer electronic functions, such as digital media players, as well.

Computers in the vehicle can be divided into two classes: those for which the primary purpose is the control of mechanical systems or subsystems, and those for which the purpose is information or entertainment. The former tend to be mission critical, hard real-time systems. They include powertrain controllers and various chassis systems, such as brakes and traction controllers and also safety systems, such as airbag controllers. They also include controllers for auxiliary systems such as the instrument cluster, lights, locks, power windows, and comfort and convenience features such as climate control and power seats.

Hard real-time control of vehicle mechanical systems represents the minimalist end of the software world. It is static software that remains unchanged for the life of the vehicle and for most systems a fairly small amount of code is involved, by today's standards. For example, Windows 98 comprises 13 million lines of code [140], but the amount of code in the most complex controller in an automobile is between 200 000 and 500 000 lines of code. Much of the complexity in this software arises from timing constraints and from the need to incorporate extensive diagnostics to prevent random hardware failures from having unintended consequences.

The powertrain (engine, transmission, and emission control systems) software is generally the most complex control software in the vehicle. Since most of the variables involved in engine control represent continuous quantities, this software makes heavy use of floating point arithmetic, unlike most of the other software in the vehicle. The powertrain software controls ignition timing for the engine, the quantity and timing of fuel delivery, the function of various emission subsystems, and the timing and quality of transmission shifting. It also performs extensive diagnostics, much of which is mandated by federal regulation [141]. The extent of the powertrain software depends on the specific engine and transmission installed in a vehicle, but there are typically over 100 functions that are controlled by this software, each of which depends on the inputs of several sensors. In addition to the code there are as many as 20 000 calibration constants that are required to tune and match the specific equations used to control a particular powertrain variant. These data plus the control code may be up to a megabyte in size.

Safety and chassis control includes the software for antilock brake systems, traction control systems, suspension systems, airbag controllers, and related vehicle dynamics and safety systems. Like the powertrain software, it is highly time-critical.

Comfort and convenience features include a large number of functions that are not critical to the operation or control of the vehicle but provide functionality that the occupants of the vehicle expect. Most of this software is based on discrete state controllers and is often limited in the functionality that it provides. Nevertheless, even in the simplest cases there are significant requirements for diagnostics and fault management. An example of a limited function that is nearly self-contained is the software that controls the driver and passenger seat heaters. A state diagram for this function is shown in Fig. 3. This software controls the current to heating elements in the seats to achieve a designated temperature set point that is determined by the state of a switch for the corresponding seat (OFF, LOW, or HIGH). It must also monitor the state of the ignition key position so that the seat heaters are only activated when the key is in the ON position. In addition, the software outputs the state of the seat heater to two LEDs for each seat. The same software must also monitor the heater, temperature, and switch circuits for open or short conditions and turn the heater circuit off if any of those faults are detected in order to prevent overheating of the seat.

This function is self-contained, except for the requirement to monitor the state of the ignition switch. If this signal is presented to the module as an analog signal, the requirements can be met with about 1 K of code. If the ignition state were read from the vehicle network, the code would become an order of magnitude larger, because the network interface code is more complex than the entire task of this module.

Infotainment software comprises software in information systems, including navigation, and in entertainment systems, such as the audio system and family entertainment center. It includes components that have a significant user interface in contrast to the software in the basic vehicle control systems. For this reason, it is often closer to traditional computer software than the other embedded software in the vehicle.

The most recent area of development in automotive software are functions that support the connection of the vehicle to external devices and services. This area falls into two categories: software that supports the connection of consumer devices to the vehicle and software that supports

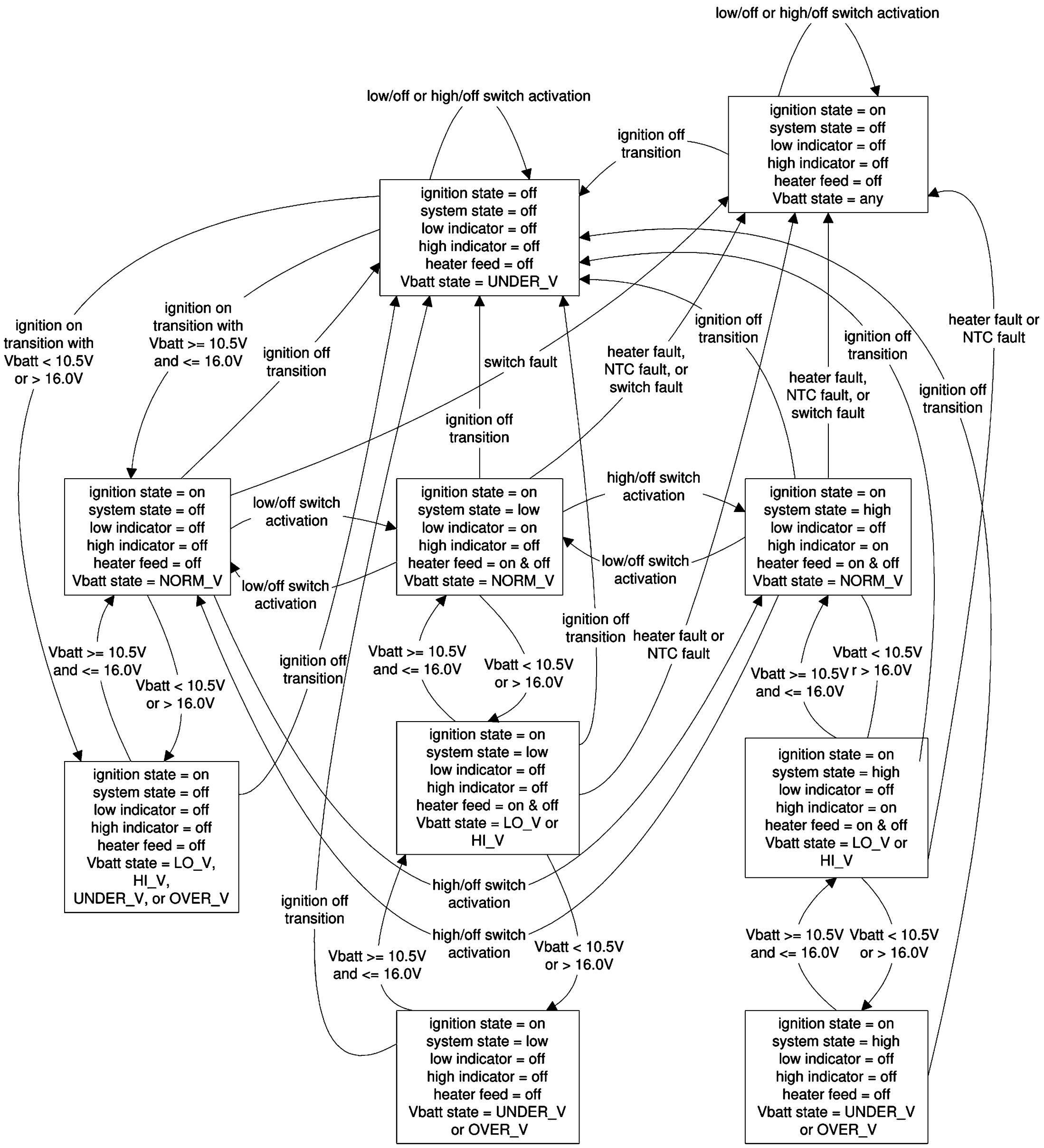

Fig. 3. ***Heated seat controller state diagram.***

remote or roadside services that connect to the vehicle through wireless channels. Software that allows consumer devices, such as cell phones and music players, to connect to the vehicle's entertainment system is rapidly becoming common, and software that connects the vehicle to roadside infrastructure is expected to appear in the near future as a result of the U.S. Department of Transportation Vehicle and Infrastructure Integration Initiative [132].

One of the most challenging areas for automotive software design is the desire to integrate the control of consumer devices with the vehicle system [142], allowing the occupants to use these devices in a way that is convenient and safe. The first application in this area was hands-free cell phone control integration. With the advent of Bluetooth^{TM} wireless technology enabled phones, it is possible for a user to enter the car, while in the midst of a call and have the call transfer to the car's audio system in a way that is transparent to the user and does not require any interruption in the call. More elaborate applications would allow an address from the contact list in the phone to be transferred to the vehicle's navigation system as a destination, short message service (SMS) messages and e-mail to be read over the car's audio system using text-to-speech software and so on. In the most general case, any service on the consumer device could be made available using the vehicle's human machine interface.

Apart from the problems of designing the software to provide the basic services—such as text-to-speech—there are three problems that must be addressed in designing software to integrate consumer devices and services to a vehicle: support for the multitude of protocols used by different consumer devices, security, and ensuring that the use of the devices does not compromise safety due to a distracting user interface.

A related area is connecting the vehicle to external services, an example of which is automotive telematics [129]. Telematics services, in this context, may take two forms: remote services and roadside assistance services. Examples of remote services are remote diagnostics or remote door unlock services, while examples of roadside assistance services include refueling or tire replacement services—where the service call is made at the touch of a button built into the vehicle. This area has seen a great deal of activity in the last ten years. Initially, the emphasis was on providing remote services, such as traffic information, off-board navigation and concierge services, but more recently active safety applications, such as collision avoidance at intersections are being considered. This is an area where software standards are important, since a market fragmented by numerous service providers and numerous platforms does not provide the necessary momentum for the technology to take off. As a result, there have been significant standardization efforts in this area, which will be discussed later in the paper.

Given the differences between control and infotainment software described above, it is not surprising that the issues facing the vehicle control software (mainly powertrain and chassis control software) are somewhat different from those facing infotainment and telematics software. The primary issue in the control domain is the increasing number of interactions between different components of the system. The control modules were originally designed as standalone components, but they are becoming increasingly dependent on other components in the vehicle as software defined features are added that depend on the vehicle state for their operation. For example, an "easy exit" feature has been added to some power seats that moves the driver's seat a small distance to the rear when he or she exits the vehicle. This feature depends on knowing whether the key is in the ignition and whether the door is being opened for its correct operation. Thus, the power seat control software must interact with the module that senses the state of the ignition key and with the door module.

Even the simplest systems interact with a large number of other systems. For example, in some vehicles, a central locking system has to interact with 18 other systems (Fig. 4). This is more of an issue than it would appear at first glance, because the interacting modules, and the software in them, may be designed by different suppliers who may in fact be competitors. Additionally, the collection of modules will differ between different vehicle lines and perhaps even within vehicle lines depending on the options present on a given vehicle. Thus, it becomes increasingly important to specify the behavioral interfaces between different modules with considerable precision, as well as to use a software architecture that separates the interface code from module specific code.

Most of the current modules in a vehicle have a software architecture that is not structured or that is structured along functional lines. A typical example is shown in Fig. 5. Although the software has distinct blocks, none of the blocks are independent of the hardware platform. Moreover, there is generally an unrestrained use of global variables and a lack of well-defined interfaces between the different components. This makes it difficult to change one component without affecting other components in the electronic control units (ECU). Where

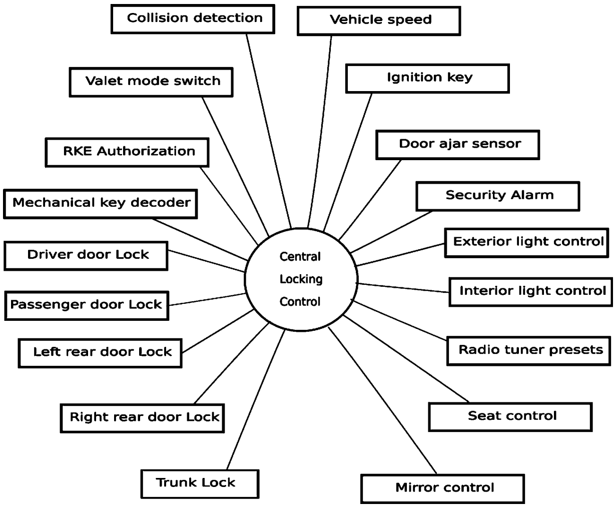

Fig. 4. *Central locking system context diagram.*

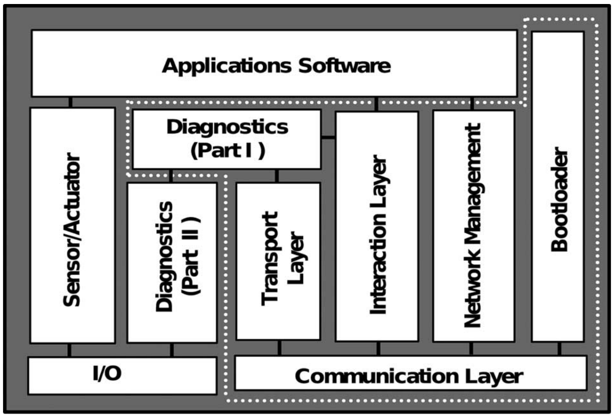

Fig. 5. *A generic module architecture.*

the interfaces are defined, they are normally specific to that module.

Another issue is security. Because the vehicle control software is static code in Flash ROM that is never modified (except in special circumstances at the dealership), security is less of an issue than it is in a personal computer. That is not to say that this software could not be made to misbehave if fed well-designed inputs out of the normal range, but there is little opportunity to add a virus or worm to the code. The entertainment and telematics systems, on the other hand, are likely in the very near future to be designed to allow applications to be added after the vehicle is manufactured. This creates a more significant possibility that malware could find its way into these systems. Bruce Schneier has proposed a scenario where the connection of a Bluetooth phone to the vehicle human machine interface provides an opportunity for a Bluetooth phone in an adjacent vehicle to pass software that would disable the vehicle navigation system [143].

Finally, there is also significant pressure on the auto manufacturers to make vehicle electronic systems, specifically the information and entertainment systems, upgradable during the life of the vehicle. This poses significant business and technology challenges since there is a big difference between vehicle life cycles and consumer electronic life cycles [127]. Further, as vehicles incorporate more consumer electronics features, this disparity becomes increasingly evident, making vehicle electronics features appear more outdated. The solution to this problem is seen to be upgrading vehicle entertainment systems through the addition of new software and in some cases new hardware as well. This, however, requires a careful architecting of the vehicle software to ensure that upgrades can be accomplished without affecting existing functionality.

Several trends are apparent in response to the issues discussed above. There are concerted efforts between automakers and suppliers to standardize the interfaces between components in different vehicle software domains. In the control software domains particularly, there are efforts in many companies to move to model-based software methodologies. Additionally, as applications emerge that affect vehicle safety, there is a move toward time-triggered architectures [144] and time-triggered network protocols. Each of these will be discussed in turn.

One of the earliest efforts at standardizing automotive software involved the protocols on in-vehicle networks, such as J1850 and controller area network (CAN). The former was carried out by SAE International [145] and the latter was created by Robert Bosch Gmbh and submitted to ISO as an automotive standard [146]. This was driven by the need to standardize the physical layer of these networks, as well as the firmware implemented protocol layers. Network protocol-layer standardization was extended to network management and operating systems in the OSEK effort [147]–[149]. OSEK compliant operating systems are now the norm for ECUs that are primarily concerned with vehicle control. The OSEK specification has limits, however, when it comes to the infotainment domain. In the first place, the operating system that it specifies is designed to handle a statically linked set of tasks with fixed, predetermined memory requirements [148]. This makes it unsuitable for applications that deal with external services such as telematics applications.

The need to incorporate more elaborate hardware and software in the infotainment arena led to the formation of another standardization effort known as the automotive multimedia interface collaboration (AMI-C), a group consisting of eight major automakers and a large number of automotive suppliers [150]. This group took a different approach to software standardization than the OSEK effort. There was no attempt to standardize the processor or operating system. Instead, a middleware layer was defined based on Java [151] and the platform defined by the OSGi Alliance [152]. This architecture presumes a platform capable of dynamic memory allocation and is intended to provide the capability of installing applications and services from remote providers while the system is running. The use of the OSGi framework allows remote management of services that are downloaded to the vehicle, and thus provides support for telematics applications. The AMI-C specification extends the OSGi platform by defining a set of services that provide access to vehicle status and diagnostic information, as well as the vehicle's human machine interface and some application services such as off-board navigation [153], [154].

The AMI-C architecture is shown in Fig. 6. An important property of this architecture is that it is a layered architecture that separates the application layer from the platform specific code. The principle of using a layered architecture is becoming increasingly important in

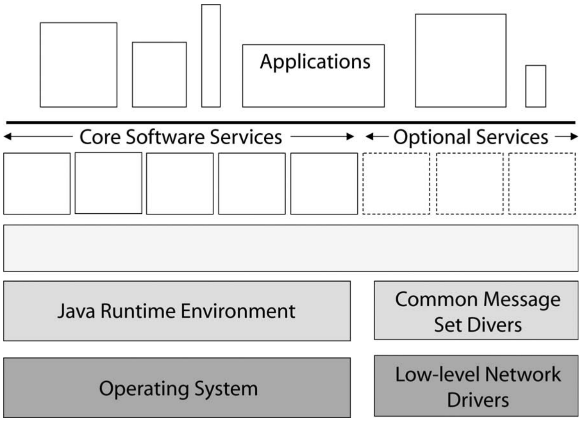

Fig. 6. ***AMI-C architecture.***

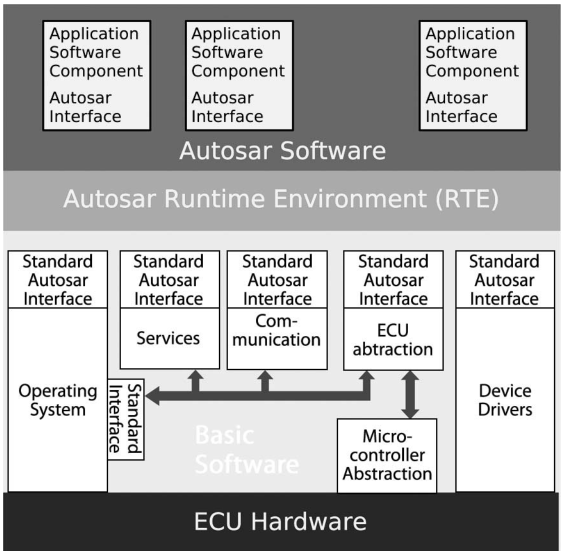

Fig. 7. ***AUTOSAR proposed software architecture.***

automotive software. A more recent standardization effort, which extends the service-based middleware layer concept to vehicle control software, is exemplified by AUTOSAR [155], [156]. AUTOSAR intends to standardize a middleware layer that provides an interface between the hardware/operating system layer and applications in control modules. Fig. 7 illustrates the AUTOSAR architecture, as described in [78].

As mentioned earlier in the context of product lifecycle disparity, automotive product development times are notably long relative to other consumer product development times [127]. In the software arena, one of the reasons for this is that little software development is done until hardware becomes available. The desire to move the engineering effort involved earlier in the product design cycle has led to an emphasis on model-based software design [157], [158]. Tools such as Simulink/Stateflow from Mathworks [159] and UML [160] are becoming widely used in the automotive industry. The advantage of model-based development is that it allows software design and coding to proceed independently of hardware development, and thus allows it to occur earlier in the product development process. It also allows designs to be tested against the model prior to implementation in hardware, and thus allows errors to be caught earlier in the process, when they are less expensive to fix. This is especially valuable when hardware in the loop (HIL) technologies are used, whereby models are executed in real-time against actual hardware modules. HIL-based module testing can be carried out in two ways: a model of the controller can be executed against the actual hardware that it controls, allowing the control algorithms to be debugged before they are implemented, or when the controller is implemented in a prototype module, it can be executed against a model of the hardware system that it controls. The latter is especially important in automotive development because the hardware environment is essentially the entire vehicle, which is normally not available until late in the program.

Initial efforts to introduce model-based engineering techniques to the automotive software development process have often fallen short of expectations because of the problem of model maintenance. In order for software models to be of use, they must be consistent with the code that they model. There is, however, a tendency for models and software to drift out of synchronization as changes are made to the code that are not reflected in the models. The best way around this problem is to automatically generate the code from the models in the first instance, and then to make changes in the models rather than in the software, regenerating the code with each change. Unfortunately, the use of automatically generated code is not widespread because of performance and memory size issues. Automatically generated code typically requires additional support code to execute in a production environment and this support code can easily represent an unacceptable overhead in memory requirements, particularly for simple controllers that only contain a small amount of code.

Initially, in-vehicle software did not involve any functions that were critical to the safe operation of the vehicle. Now, there is an increasing trend toward replacing mechanical controls by electronic controls in safety-critical systems such as braking, throttle control, and even steering. It is generally recognized that the current network and software architectures are not adequate to provide the high reliability required by such systems. Because of this, there is a trend toward using time-triggered architectures [144], [161]. In a time-triggered architecture, communications and tasks are statically scheduled, rather than executing in response to asynchronous events. Such architectures, thus, have greater predictability than event triggered architectures. Much of the work related to time-triggered architectures has revolved around network protocols. There are several proposals for time-triggerred protocols for automotive networks. These include time triggered CAN [162], [163] and FlexRay [164]. In addition to time-triggerred networks, time-triggered operating systems have also been developed. There is a time-triggered version of OSEK called OSEKtime, for example, [165] and [166]. This is a statically scheduled RTOS with minimal services. Static scheduling is designed to make the execution timing of applications predictable.

VII. CONCLUSION

The Model T changed society by bringing personal mobility to the majority of people, and set the standard for desirable, affordable transportation in the first part of the twentieth century. This paper has proposed that advances in control, computing, and communications will shape the expectations of the automotive consumer in the twenty-first century, where the essential characteristics of the "new Model T" are environmental stewardship, safety, economy, and connectedness. ■

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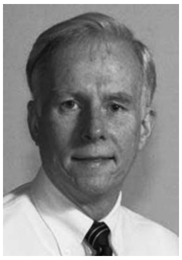

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